Birthplace of the São Francisco Craton, Brazil: Evidence from 3.603.64 Ga Gneisses of the Mairi Gneiss Complex

Citation for published version:
Oliveira, EP, Mcnaughton, NJ, Zincone, SA & Talavera, C 2020, 'Birthplace of the São Francisco Craton, Brazil: Evidence from 3.603.64 Ga Gneisses of the Mairi Gneiss Complex', *Terra nova*. https://doi.org/10.1111/ter.12460

Digital Object Identifier (DOI):
10.1111/ter.12460

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Terra nova

DR ELSON PAIVA OLIVEIRA (Orcid ID : 0000-0002-3501-0335)

Article type : Research Article

Birthplace of the São Francisco Craton, Brazil: Evidence from 3.60-3.64 Ga Gneisses of the Mairi Gneiss Complex

Elson P. Oliveira[a]*, Neal J. McNaughton[b], Stefano A. Zincone[c], Cristina Talavera[d]

[a]Institute of Geosciences, University of Campinas, Campinas 13083-855, Brazil

[b]John de Laeter Centre, Curtin University, Perth WA 6845, Australia

[c]Department of Geology, Federal University of Ouro Preto, Ouro Preto 35400-000, Brazil

[d]School of Geosciences, University of Edinburgh, Edinburgh EH9 3FE, UK.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/TER.12460

*Corresponding author at: Institute of Geosciences, University of Campinas, *13083-855* Campinas, Brazil.
Phone: +55-1935215158; E-mail address: elsonepo@unicamp.br

Abstract

Records of Earth's primitive crust are scarce. Eoarchean (older than 3.6 Ga) banded mafic to felsic gneisses have been discovered in the São Francisco Craton, Brazil, pushing back by over 100 million years the oldest gneisses known to date in South America (3.5 Ga). Zircon U-Pb data yield rock ages from 3598 Ma to 3642 Ma with a few ca. 3.65 to 3.69 Ga grains suggesting even older rocks in the area. Zircon grains show significantly negative to nearly chondritic initial εHf values and two-stage model ages from 3.82 Ga to 4.33 Ga, which may indicate the existence of a recycled Hadean to early Eoarchean crust in the region. The felsic gneisses are chemically similar to the low-pressure Tonalite-Trondhjemite-Granodiorite association whereas the mafic gneisses have geochemical signatures that resemble within-plate basaltic andesite to andesite of Iceland (icelandites). The results are relevant to constrain the composition of Earth's first continental crust.

1 | INTRODUCTION

The nature of Earth's primitive crust and the mechanisms responsible for its formation and evolution are key issues to understanding the origin and differentiation of the mantle, continental crust, formation of the first cratons and when plate tectonics began in our planet. The oldest rocks on Earth are mostly gneiss complexes that occur in cratonic blocks within high-grade metamorphic terrains of Eoarchaean to Hadean ages (older than 3.6 Ga; Condie, 2019). Those gneisses are largely sodic and belong to the tonalite-trondhjemite-granodiorite (TTG) series, which are regarded to have formed at low, medium and high pressures (Moyen, 2011). However, the study of those old rocks is limited because of scarce exposure and highly deformed nature of the rocks (Dey et al., 2017). In South America, the oldest rocks (3.3-3.5 Ga) are TTG gneisses from the São Francisco craton (Martin et al., 1997; Nutman and Cordani, 1993; Dantas et al. 2010) and Borborema Province (Dantas et al., 2004). This study reports new zircon U–Pb ages, zircon in-situ Hf isotope data and whole-rock geochemistry for recently discovered gneisses in the São Francisco Craton that are over 100 million years older than the oldest gneisses known so far. We further discuss the implications of these findings for the nature of the earliest continental crust and its sources.

2 | GEOLOGICAL SETTING AND FIELD RELATIONS

The São Francisco Craton (SFC) is the second largest craton in South America after the Amazonian craton. The SFC is composed of Archaean to Palaeoproterozoic basement gneisses and greenstone belts covered by late Palaeoproterozoic to Neoproterozoic cratonic sedimentary basins (Alkmim and Martins-Neto 2012; Heilbron et al., 2017). The basement rocks of the SFC occur in the Gavião, Serrinha and Jequié blocks, Itabuna-Salvador-Curaçá orogen and in the Belo Horizonte domain (Figure 1).

To date, the Gavião block has the oldest rocks of the SFC. The block is composed of TTG gneisses, dismembered greenstone belts and several granitic plutons (Zincone et al., 2016; Medeiros et al., 2017; Teixeira et al. 2017). The oldest rocks in the Gavião block are 3537 Ma gabbro-diorite enclaves within Palaeoarchaean gneisses of the northern part of the block (Dantas et al., 2010). The next older rocks are the Sete Voltas, Boa Vista-Mata Verde and Bernarda TTG gneisses (3403-3372 Ma - Martin et al, 1997; Nutman and Cordani, 1993; Peucat et al., 2002).

FIGURE 1 HERE

The gneisses described here occur within an area mapped as the Mairi Gneiss Complex (Figure 1). This complex crops out for over 400 km along the eastern edge of the Gavião block, and is composed of amphibolite facies grey gneisses and diorite to gabbro bodies (Loureiro et al., 1991). The complex is poorly studied and only a few zircon Pb evaporation ages of ca. 3.4 Ga (Mougeot, 1996) and 3.04 Ga (Peucat et al., 2002) are available. Three outcrops of Eoarchaean gneisses were found close to town of Piritiba (Figure 1). The first is banded gneiss 17ED-14, which is composed of biotite-hornblende tonalitic to granodioritic paleosome and leucogranite neosome (Figure 2a,b). Banded gneiss 18DE-17 is located 2 km to the south of 17ED-14, and is composed of medium-grained hornblende tonalitic to dioritic mafic bands in structural conformity with felsic bands of granodioritic gneiss (Figure 2c). The third outcrop (18DE-1) is located near Piritiba and consists of large xenoliths of biotite tonalitic gneiss within biotite granite (Figure 2d).

FIGURE 2 HERE

3 | ANALYTICAL RESULTS

Analytical methods are summarized in Appendix S1, representative zircon CL images are in Appendix S2, and results table for U-Pb ages, Hf isotopes and whole-rock geochemistry in Appendixes S3, S4 and S5, respectively.

3.1 | Zircon U-Pb ages

Zircon grains from four Eoarchaean gneisses were analysed for age dating: one sample from outcrop 17ED-14 (granodioritic gneiss paleosome 17ED-14.1; Figure 2a,b), two samples from 18DE-17 (dioritic gneiss dark band 18DE-17 and granodioritic gneiss felsic band 18DE-17a; Figure 2c) and one sample from outcrop 18DE-1 (xenolith of tonalitic gneiss 18DE-1.2; Figure 2d). Concordia plots for four additional samples are shown in Figure 4 because the age of one sample (leucogranite neosome 17ED-14b) is relevant to understanding a few younger ages observed in the Eoarchaean gneisses, and three others (gneisses 18DE-4.2, 18DE-16.1 and 18DE-20) contain older inherited zircon grains, which indicate the likely occurrence of older rocks in the area.

Zircon grains from the granodioritic gneiss paleosome 17ED-14.1 (Figure 3a, b) were analysed by LA-ICP-MS and eleven analyses on zircon cores yield the upper intercept age of 3626±15 Ma (MSWD=1.09) (Figure 3a). Additional eleven concordant zircon cores were analysed on the SHRIMP and the results are separated into two age groups (Figure 3b). The younger group of three analyses gives a concordia age of 3521±27 Ma (MSWD=0.68). Excluding analysis 4.1, seven older grains give a concordia age of 3637.5±14 Ma (MSWD=5.6, 1s). However, because MSWD value is above the recommended value for 7 analyses (Wendt and Carl, 1991; Spencer et al., 2016), two separate concordia age calculations were done with the older grains; the first one by using four analyses with the oldest $^{207}Pb/^{206}Pb$ ages and the second with three analyses of the immediate younger $^{207}Pb/^{206}Pb$ ages. The results are 3642.2±4.7 Ma (MSWD=1.7; probability=0.19; 1s) and 3616±7.3 Ma (MSWD=2.4; probability=0.13; 1s) for the older and younger groups, respectively (Figure 3b). Within uncertainty limits the former concordia age (3642 Ma) is similar to the LA-SF-ICP-MS age of 3626±15 Ma. Therefore, we consider 3642 Ma as the igneous age of the gneiss protolith. Fifteen zircon grains from the leucogranite neosome 17ED-14b (Figure 4) gave the 3551±27 Ma upper intercept age (MSWD=3.5; n=15), which, within uncertainties, matches the younger age 3521±27 Ma observed on zircons from the host paleosome.

FIGURE 3 HERE

Zircon LA-ICP-MS U-Pb data for the dioritic gneiss 18DE-17 are shown in Figure 3c. The majority of zircon analyses (54) are concordant (<5% discordance). Seventeen of these analyses on zircon cores give the pooled mean $^{207}Pb/^{206}Pb$ age of 3589.9±3.6 Ma (MSWD=0.33; 2s; probability=0.994). Eight older analyses on zircon cores, less than 2% discordant yield the concordia age of 3627.9±8.6 Ma (MSWD=0.051, 2s, probability=0.82). An additional twenty

SHRIMP analyses were done on zircons from this sample, of which sixteen analyses are concordant (<5% discordance). Two age groups were recognised (Figure 3d). The younger group of three analyses yields a concordia age of 3511±8 Ma (MSWD=1.9, probability=0.16; 1s). The older group of thirteen analyses comprises three analyses older than 3630 Ma, nine between 3600 and 3630 Ma and one analysis younger than 3600 Ma. The analyses between 3600 and 3630 Ma are all from zircon cores and produce a concordia age of 3612.1±4.4 Ma (MSWD=2.2, probability=0.14; 1s). The three oldest analyses yield a pooled mean $^{207}Pb/^{206}Pb$ age of 3637.7±7.7 Ma (MSWD=0.078, probability=0.92, 1s) but no reliable concordia age (MSWD=3.9). We suggest ca. 3638 Ma as the crystallisation age of the igneous protolith.

Fifty-five analyses on forty-six zircon grains from the granodioritic gneiss 18DE-17a were done by LA-SF-ICP-MS (Figure 3e). The most concordant analyses (<5% discordance) spread along the concordia and can be grouped into three age clusters. The oldest one contains twenty core analyses, which yields a regression with an upper intercept age of 3598.8±6.8 Ma (MSWD=1.6; 2s; probability=0.055). The youngest age cluster comprises three zircon core analyses and yields an upper intercept age of 3441±24 Ma (MSWD=0.112; 2s). The third cluster of zircon core analyses is intermediate in age between the two others and no age was calculated because those zircon grains may have lost Pb from the older zircon grains. We suggest ca. 3600 Ma as the igneous age of the gneiss protolith and the younger age ca. 3440 Ma as Pb loss related to a regional, or local event (e.g. emplacement of granodioritic gneiss 18DE-20 protolith at 3454±13 Ma; Figure 4d).

Sixty-six zircon grains of the biotite gneiss xenolith 18DE-1.2 were analysed by LA-SF-ICP-MS (Figure 3f). Thirty-five of eighty-one analyses are concordant (<5% discordance). The upper intercept age of these analyses yield the age 3578±16 Ma (MSWD=3.4; 2s; probability=0.000), a pooled mean $^{207}Pb/^{206}Pb$ age of 3551±13 Ma (MSWD=30; probability=0.000) and no concordia age. Six older spot analyses on oscillatory zoning zircon cores yield a concordia age of 3609.7±8.5 Ma (MSWD=0.65; 2s; probability=0.42), which is suggested to be the igneous protolith age. Another younger age group of ten core analyses yields a discordia of 3557±16 Ma (MSWD=2.2; 2s), which is similar to the age estimate for leucogranite neosome 17ED-14b (3551±27 Ma; Figure 4a).

Ages for other regional gneisses are shown in Figure 4 along with single ages for the oldest zircon grains they contain.

FIGURE 4 HERE

3.2 | Zircon Hafnium isotope

Zircon Hf isotope data for 17ED-14.1, 18DE-17, 18DE-1.2 and 18DE-17a gneisses are presented in Appendix S4 and in Figure 5, along with data for a few older zircon grains in the regional gneisses, 18DE-16.1, 18DE-20 and 18DE-4.2. A summary of ages and Hf results are shown in Table 1.

Zircon analyses show chondritic to unradiogenic $\varepsilon_{Hf(t)}$ values (-6.6 to -0.3) (Table S2; Figure 5) suggesting that the felsic component of the rocks was from a recycled ancient crust rather than a juvenile one. One-stage (T_{DM1}) and two-stage (T_{DM2}) depleted mantle model ages are ~3770-4020 Ma (mostly within 3850-3950 Ma) and ~3850-4120 Ma (mostly within 3900-4100), respectively (Table S2), and chondritic mantle model ages (T_{CHUR}) vary from ca. 3620 to 3960 Ma. Considering that the rocks were likely from a recycled crust, this may indicate the existing of the Hadean to early Eoarchean crust in the São Francisco craton. The inherited older zircons have $\varepsilon_{Hf(t)}$ values of -8.6 to -4.9, T_{DM1} and T_{DM2} in the interval ~4000-4360 Ma and T_{CHUR} ~3930-4160 Ma suggesting they have grown from magmas derived from even older sources of Hadean age.

FIGURE 5 HERE

TABLE 1 HERE

3.3 | Whole-rock geochemistry

Whole-rock major and trace elements data were obtained for ten samples of Eoarchaean gneisses. Petrography and major element composition of these gneisses show they can be divided into two groups: one mafic (48-62 wt% SiO_2) and another felsic (SiO_2> 67wt%). The chemical characteristics of these groups are shown in Figures 6 and 7. The former group is represented by tholeiitic dioritic to hornblende tonalitic gneisses, whereas the other comprises calc-alkaline biotite tonalitic to granodioritic gneisses, with rare hornblende. When major and trace elements are combined, the felsic gneisses are TTGs and plot in the fields of high-heavy rare earth elements (REE) TTG, or low (LP) to medium (MP) pressures TTG (Figure 7). The mafic gneisses share some geochemical characteristics with the LP TTG but their Ca-K-Na relationship, REE patterns with higher heavy-REE abundances, less fractionated La/Yb, pronounced negative Eu anomalies and high concentrations of high field strength elements (Figure 7) resemble icelandites.

FIGURE 6 HERE

FIGURE 7 HERE

4 | DISCUSSION

Earth's Hadean to Eoarchaean gneisses show complex history of zircon crystallisation ages owing to the younger metamorphic/tectonic events they have undergone (e.g. Black et al., 1986; Compston and Kröner 1988; Bowring et al. 1989; Liu et al. 1992; Iizuka et al., 2006), and so are the gneisses studied here. The Eoarchaean ages (ca. 3600-3640 Ma) for the Mairi Complex gneisses of the Piritiba area indicate they are South America's oldest gneisses so far. Rocks even older might be found in the area as evidenced by ca. 3650-3690 Ma relict zircon grains in three nearby younger gneisses and two-stage zircon Hf model ages as old as ca. 4360 Ma.

The Mairi Complex Eoarchaean rocks consist of felsic gneisses of the TTG suite and mafic gneisses of dioritic to tonalitic composition, sometimes forming banded gneisses of the two types. The felsic gneisses have geochemical characteristics similar to the low (LP) to medium (MP) pressure TTG (Figure 7). The first occurrence of LP and MP TTGs on Earth's continental crust precedes that of the high-pressure TTG, and the studied rocks confirm this tendency (Figure 8a) suggesting that Eoarchaean continental crust was not thick enough to stabilize garnet in the melting residue (e.g. Martin, 1993) and allow for origin of the high-pressure TTG. The mafic gneisses, on the other hand, have geochemical characteristics similar to icelandites (Figures 6,7), a volcanic rock of basaltic andesite to andesite composition that is interpreted to have formed by fractionation of basaltic magma at low pressures (Carmichael, 1964; Grove and Kinzler, 1986), or mixing of basaltic and felsic magmas (Carmichael, 1964; Nicholson et al., 1991; Mancini et al., 2015). The average Th/Nb value of the mafic gneisses (0.12) is consistent with their origin in a within-plate setting (Figure 8).

FIGURE 8 HERE

Zircon grains from the studied gneisses yield chondritic to unradiogenic $\varepsilon_{Hf(t)}$ values (Figure 5) with all values being more negative than the chondrite values. Zircon Hf model ages yield early Eoarchaean to Hadean ages for the studied samples. These features provide evidence for crystallization of the igneous protoliths of the gneisses from magmas derived from melting of older sources. These sources could be related to a major event of mantle differentiation and continental crust formation as deduced from a cluster of zircon ages from the literature between 3.8-3.9 Ga with positive $\varepsilon_{Hf(t)}$ values (Figure 5). This raises the question of whether the Mairi complex gneisses preserve evidences of the initial differentiation of Earth's mantle as for the

^{146}Sm-^{142}Nd isotopic system, or has the mantle been completely homogenised in the south hemisphere as suggested by some authors (Wainwright et al., 2018)? This and other questions about South America's primitive crust will be addressed in the future as our study progresses.

ACKNOWLEDGEMENTS

Research grants from FAPESP (#2012/15824-6 and #2018/25465-0), FAPESP-ATN (Australian Technology Network of Universities #2014/50353-0) and CNPq (#305658/2015-8) are acknowledged. Peng Peng and colleagues at Institute of Geology and Geophysics, Beijing, helped discuss the Hf isotope results. The comments of Jesse Reimink, the Associate Editor of Terra Nova and an anonymous reviewer greatly improved the original manuscript.

DATA AVAILABILITY STATEMENT

Data related to this submission is available as supplementary files.

REFERENCES

Alkmim F.F., Martins-Neto M.A., 2012. Proterozoic first-order sedimentary sequences of the São Francisco craton, eastern Brazil. Marine and Petroleum Geology 33, 127–139.

Barbosa N., Teixeira W., Leal L.R.B., Menezes Leal A.B., 2013. Evolução crustal do setor ocidental do Bloco Arqueano Gavião, Cráton do São Francisco, com base em evidências U-Pb, Sm-Nd e Rb-Sr. Geologia USP, Série Científica, 13, 63–88.

Barker F., Arth J.G., 1976. Generation of trondhjemitic – tonalitic liquids and Archaean bimodal trondhjemite-basalt suites. Geology 4, 596-600.

Black, L.P., Williams, I.S., Compston, W., 1986. Four zircon ages from one rock: the history of a 3930 Ma old granulite from Mount Sones, Enderby Land, Antarctica. Contributions Mineralogy and Petrology 94, 427-437.

Bowring S.A., Williams I.S., Compston W., 1989. 3.96 Ga gneisses from the Slave Province, Northwest Territories, Canada. Geology 17, 971-975.

Carmichael I.S.E., 1964. The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. Journal of Petrology 5, 435-460.

Compston W., Kröner A., 1988. Multiple zircon growth within early Archaean tonalitic gneiss from the Ancient Gneiss Complex, Swaziland. Earth Planetary Science Letter 87,13–28.

Condie K.C., 2019. Earth's Oldest Rocks and Minerals. In: Martin J. Van Kranendonk, Vickie C. Bennett and J. Elis Hoffmann (Eds). Earth's Oldest Rocks, 2nd Edition. Elsevier, Chapter 11, 239-253.

Dantas E.L., Brito Neves B.B., Fuck R.A., 2010. Looking for the oldest rocks of South America: Paleoarchean orthogneiss of the Sobradinho Block, northernmost foreland of the São Francisco Craton, Petrolina, Pernambuco, Brazil. VII South American Symposium on Isotope Geology (SSAGI), Brasilia, p. 137-140. S0136.

Dantas E.L., Van Schmus W.R., Hackspacher P.C., Fetter A.H., Brito Neves B.B., Cordani U., Nutman A.P., Williams I.S., 2004. The 3.4–3.5 Ga São José do Campestre massif, NE Brazil: remnants of the oldest crust in South America. Precambrian Research 130, 113-137.

Dey S., Topno A., Liu Y., Zong K., 2017. Generation and evolution of Palaeoarchaean continental crust in the central part of the Singhbhum craton, eastern India. Precambrian Research 298, 268–291.

Griffin W. L., Wang X., Jackson S. E., Pearson N. J., O'Reilly S. Y., Xu X., Zhou X., 2002. Zircon chemistry and magma mixing, SE China: in-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. Lithos 61, 237–269.

Grove T.L., Kinzler R.J., 1986. Petrogenesis of andesites. Annual Reviews of Earth and Planetary Sciences 14, 417-454.

Hawkesworth C., Cawood P.A., Dhuime B., 2019. Rates of generation and growth of the continental crust. Geoscience Frontiers 10, 165-173.

Heilbron M., Cordani, U.G., Alkmim F.F., 2017. The São Francisco Craton and Its Margins. In: M. Heilbron, U.G. Cordani, F.F. Alkmim (eds.), *São Francisco Craton, Eastern Brazil,* Springer International Publishing Switzerland, Regional Geology Reviews 2017, p. 3-13.

Heilimo E., Halla J., Hölttä P., 2010. Discrimination and origin of the sanukitoid series: Geochemical constraints from the Neoarchean western Karelian Province (Finland). Lithos 115, 27–39.

Iizuka T., Horie K., Komiya T., Maruyama S., Hirata T., Hidaka H., Windley B.F., 2006. 4.2 Ga zircon xenocyst in an Acasta gneiss from northwestern Canada: Evidence for early continental crust. Geology 34, 245-248.

Liu D.Y., Nutman A.P., Compston W., Wu J.S., Shen Q.H., 1992. Remnants of >3800 Ma crust in the Chinese part of the Sino-Korean craton. Gology 20, 339-342.

Loureiro H.S.C., 1991. Programa Levantamentos Geológicos Básicos do Brasil. Mundo Novo. Folha SC.24-Y-D-IV. Estado da Bahia. CPRM-Serviço Geológico do Brasil.

Mancini A., Mattsson H.B., Bachmann O., 2015. Origin of the compositional diversity in the basalt-to-dacite series erupted along the Heiðarsporður ridge, NE Iceland. Journal of Volcanology and Geothermal Research 301, 116-127.

Martin, H., 1993. The mechanisms of petrogenesis of the Archean continental crust –comparison with modern processes. Lithos 30, 373–388.

Martin H., Peucat J.J., Sabaté P., Cunha J.C., 1997. Crustal evolution in the early Archaean of South America: example of the Sete Voltas Massif, Bahia State, Brazil. Precambrian Research 82, 35-62.

Martin H., Smithies R., Rapp R., Moyen J., Champion D., 2005. An overview of adakite, tonalite Trondhjemite Granodiorite (TTG), and sanukitoid: relationships and some implications for crustal evolution. Lithos 79, 1–24.

McDonough W.F., Sun S.-S., 1995. The composition of the Earth. Chemical Geology 120, 223–253.

Medeiros E.L.M., Cruz S.C.P.,Barbosa J.S.F., Paquette J.L., Peucat J.J., Jesus S.S.G.P., Barbosa R.G., Brito R.S.C., Carneiro M.A., 2017.The Santa Izabel Complex, Gaviao Block, Brazil: Components, geochronology, regional correlations and tectonic implications. Journal of South American Earth Sciences 80, 66-94.

Menezes R.C.L., Loureiro H.S.C., Reis C., Santos F.P., Miranda D.A., Vieira R., 2018. ARIM Serra de Jacobina: PIRITIBA . Folha SC.24-Y-C-VI. Estado da Bahia. Carta Geológica-Geofísica. Salvador: CPRM, 2018, 1 mapa colorido, 100,0 x 82,0 cm. Escala 1:100.000. Programa Geologia, Mineração e Transformação Mineral.

Mougeot R., 1996. Etude de la limite Archéen-Protérozoïque et des minéralisations Au, ±U associées. Exemples de la région de Jacobina (Etat de Bahia, Brésil) et de Carajas (Etat de Para, Brésil). Thèse de l'Université de Montpellier II (306 pp.).

Moyen J-F., Laurent O., 2018. Archaean tectonic systems: A view from igneous rocks. Lithos 302–303, 99–125.

Moyen J.-F., 2011. The composite Archaean grey gneisses: Petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth. Lithos 123, 21–36.

Nicholson H., Condomines M., Fitton J.G., Fallick A.E., Grönvold K., Rogers G., 1991. Geochemical and Isotopic Evidence for Crustal Assimilation beneath Krafla, Iceland. Journal of Petrology 32, 1005–1020.

Nutman, A.P., Cordani, U.G., 1993. SHRIMP U-Pb zircon geochronology of Archaean granitoids from the Contendas-Mirante area of the São Francisco craton, Bahia, Brazil. Precambrian Research 63, 179 188.

Nebel-Jacobsen Y, Munker C, Nebel O, Gerdes O, Mezger K, Nelson D. R., 2010. Reworking of Earth's first crust: Constraints from Hf isotopes in Archean zircons from Mt. Narryer, Australia. Precambrian Research 182, 175‑186.

Oliveira, E.P., Windley, B.F., McNaughton, N., Pimentel, M., Fletcher, I.R., 2004. Contrasting copper and chromium metallogenic evolution of terranes in the Palaeoproterozoic Itabuna-Salvador-Curaçá Orogen, São Francisco Craton, Brazil: new zircon (SHRIMP) and Sm-Nd (model) ages and their significance for orogen- parallel escape tectonics. Precambr. Res. 128, 143–165.

Peucat J.J., Mascarenhas J.F., Barbosa J.S., Souza,F.S., Marinho M.M., Fanning C.M., Leite C.M.M., 2002. 3.3 Ga SHRIMP U–Pb zircon age of a felsic metavolcanic rock from the Mundo Novo greenstone belt in the São Francisco craton, Bahia (NE Brazil). Journal of South American Earth Sciences 15, 363–373.

Reimink J.R., Chacko T., Stern R.A., Heaman L.M., 2014. Earth's earliest evolved crust generated in an Iceland-like setting. Nature Geoscience 7, 529–533.

Reimink J.R., Chacko T., Stern R.A., Heaman L.M., 2016. The birth of a cratonic nucleus: Lithogeochemical evolution of the 4.02–2.94 Ga Acasta Gneiss Complex. Precambrian Research 281, 453-472.

Spencer C.J., Kirkland C.L.,Taylor R.J.M., 2016. Strategies towards statistically robust interpretations of in situ UePb zircon geochronology. Geoscience Frontiers 7, 581-589.

Teixeira W., Oliveira E.P., Marques L.S., 2017. Nature and evolution of the Archean crust of the São Francisco Craton: a review. In: Cordani,U.G, Heilbron, M., Alkmim, F. F. (Eds.). *São Francisco Craton, Eastern Brazil*. Springer International Publishing Switzerland, Regional Geology Reviews 2017, p. 29-56.

Wainwright A.N., Debaille N., Zincone S.A., 2018. Archean isotope anomalies as a window into the differentiation history of the Earth. Abstract at the conference "Differentiation: Building the Internal Architecture of Planets 2018", May 7–10, 2018, Pasadena, California. LPI contribution No. 2084, abstract #4015.

Wendt I., Carl C., 1991. The statistical distribution of the mean squared weighted deviation. Chemical Geology (Isotope Geoscience Section) 86, 275-285.

Zincone S.A., Oliveira E.P., Laurent O., Zhang H., Zhai M., 2016. 3.30 Ga high-silica intraplate volcanic–plutonic system of the Gavião Block, São Francisco Craton, Brazil: Evidence of an intracontinental rift following the creation of insulating continental crust. Lithos 266, 414-434.

FIGURE AND TABLE CAPTIONS

FIGURE 1 Geological setting of the newly discovered, oldest gneisses in the São Francisco Craton. a) The São Francisco Craton in South America and its main tectonic units (modified from Oliveira et al., 2004). G, S and J stand for Gavião, Serrinha and Jequié blocks, respectively; b) Occurrence area of the studied gneisses with outcrop location; black circles for Eoarchaean gneisses and white circles for younger gneisses with Eoarchaean inherited zircon. Geological map modified from Menezes et al. (2018).

FIGURE 2 Field aspects of Eoarchaean gneisses of the Mairi Complex. a) 17ED-14 banded gneiss with granodioritic gneiss paleosome and leucogranite neosome, locally folded; b) Detail of 17ED-14 showing the more homogeneous sampled granodioritic gneiss; c) 18DE-17 banded gneiss with the sampled dark band of dioritic gneiss and grey band of granodioritic gneiss; d) 18DE-1 xenolith of biotite gneiss within weakly deformed granite host.

FIGURE 3 Zircon U-Pb ages for Eoarchaean gneisses of the São Francisco Craton. a) LA-ICP-MS results for granodioritic gneiss paleosome 17ED-14.1; b) SHRIMP results for the granodioritic gneiss paleosome 17ED-14.1; c) LA-ICP-MS results for dioritic gneiss 18DE-17; d) SHRIMP results for dioritic gneiss 18DE-17; e) LA-ICP-MS results for granodioritic gneiss 18DE-17a; f) LA-ICP-MS results for biotite gneiss xenolith 18DE-1.2. Error ellipses are 1s for SHRIMP and 2s for LA-ICP-MS data.

FIGURE 4 Zircon LA-ICP-MS U-Pb ages of the regional gneisses close to the Eoarchaean gneisses of the Mairi Gneiss Complex. a) leucogranite neosome 17ED-14b; b, c and d are gneisses with older zircon grains.

Figure 5 Comparison of Hf isotopes of the studied samples from the Mairi Gneiss Complex, São Francisco craton, with those in Archaean and Hadean zircons from global localities (after Nebel-Jacobsen et al., 2010). Green dashed lines represent a value of the average upper continental crust (Griffin et al., 2002). Vectors indicate mafic melts ($^{176}Lu/^{177}Hf$=0.021) and felsic melts ($^{176}Lu/^{177}Hf$=0.015). DM=depleted mantle. CHUR=Chondritic Uniform Reservoir (chondritic mantle).

FIGURE 6 Composition of the Eoarchaean gneisses of the São Francisco Craton. a) AFM plot with division of tholeiitic and calc-alkaline series; b) Mg-number (in molecular proportions) vs. SiO_2; c) FeOt/MgO vs. SiO_2 with compositional fields of the tholeiite and calc-alkaline series. Grey field in all diagrams illustrates the composition of icelandites (GEOROC database - SiO_2 = 55-65wt%; Al_2O_3 < 16wt%, total FeO>8wt%). Icelandite-like, 4.02 Ga Idiwhaa tonalitic gneiss after Reimink et al. (2016).

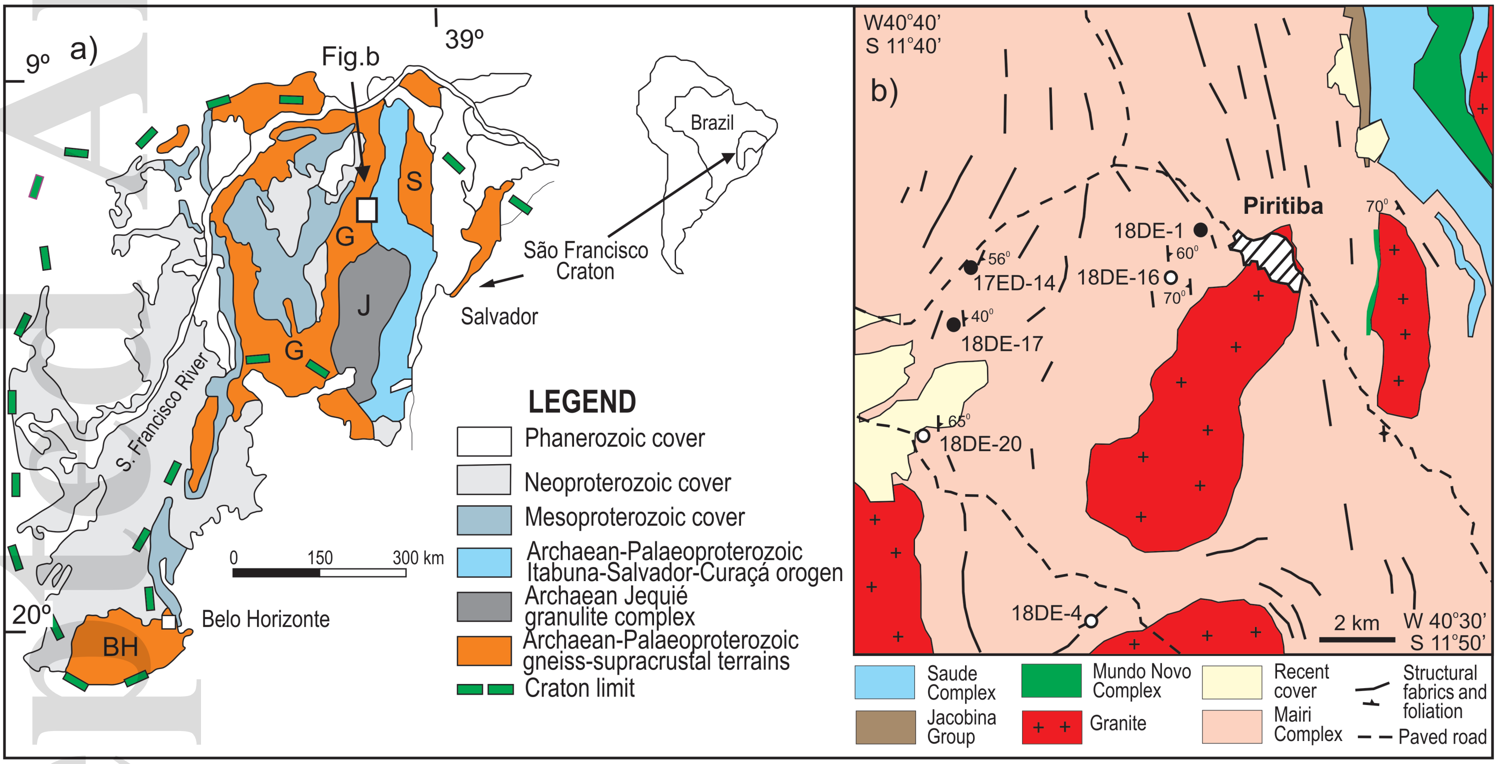
FIGURE 7 Composition of the Eoarchaean gneisses of the São Francisco Craton. a) Ternary K-Na-Ca plot showing calc-alkaline (CA) and tronhjemite (Tdh) trends from Barker and Arth (1976), and fields of Archaean TTG (shaded) and icelandites from Martin et al. (2005) and Reimink et al. (2016), respectively; b) Ternary (Ba+Sr)/1000-1/Er-Er plot to discriminate between sanukitoids and TTGs after Heilimo et al. (2010) with field for icelandites from GEOROC (SiO_2=55-65wt%; FeOt>8wt%; Al_2O_3<16wt%); c) Chondrite-normalised (McDonough and Sun, 1995) REE plot for the felsic granodioritic gneisses compared to icelandites (after Reimink et al., 2014) and TTG types as low heavy REE (HREE), medium HREE and high HREE types after Moyen, 2011); d) Same for the mafic dioritic gneiss; e) Sr-Y plot to discriminate the TTG types as high (HP), medium (MP) and low pressure (LP) after Moyen (2011) - arrow indicates fractional crystallization; f) Sr/Y vs. La/Yb plot, with TTG types and icelandites as in e).

Figure 8 Time-composition diagrams for Eoarchaean Mairi Complex gneisses. a) TTG types from Moyen and Laurent (2018); and b) Archaean mafic rocks from Hawkesworth et al. (2019); Icelandite-like, 4.02 Ga Idiwhaa tonalitic gneiss (SiO_2=57-62%) from Reimink et al. (2016). Blue and pink fields are for subduction and within-plate settings, respectively.

Table 1 Summary of the zircon U-Pb geochronology and Hf isotope data.

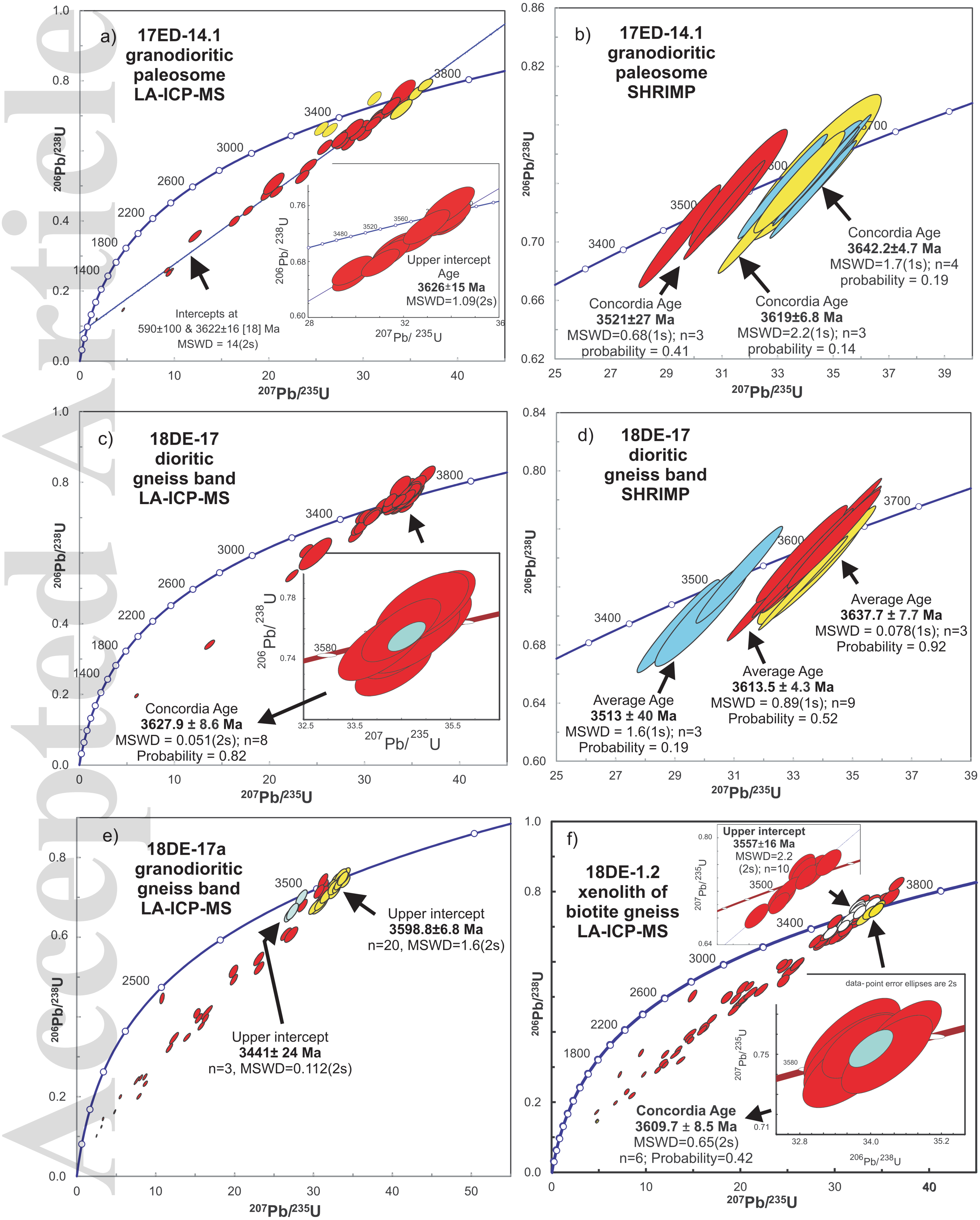
Sample number	Rock type	Sample location Latitude°	Longitude°	Age (Ma0	Geological interpretation	εHf(t)	TCHUR (Ma)	TDM2* (Ma)
17ED-14.1	granodioritic gneiss	S11.731763	W40.636936	3642	igneous age	-2.9	3817	4001
17ED-14b	leucogranite neosome	S11.731763	W40.636936	3551	migmatization age	–	–	–
18DE-17	dioritic gneiss	S11.751663	W40.642613	3638	igneous age	-2.2	3770	3887**
18DE-17a	granodioritic gneiss	S11.751663	W40.642613	3599	igneous age	-1.9	3715	3909
18DE-1.2	biotite gneiss xenolith	S11.724950	W40.576808	3610	igneous age	-2.6	3750	3941
18DE-16.1	granodioritic gneiss	S11.735874	W40.585989	3666	inherited zircon	-6.3	4021	4228
18DE-16.1	granodioritic gneiss	S11.735874	W40.585989	3680	inherited zircon	-8.6	4158	4359
18DE-20	granodioritic gneiss	S11.770812	W40.648516	3649	inherited zircon	-4.9	3928	4139
18DE-4.2	granodioritic gneiss	S11.824419	W40.604466	3688	inherited zircon	-4.8	3960	4169

*TDM2 - two stage depleted mantle model age for a felsic magma. ** one-stage model age

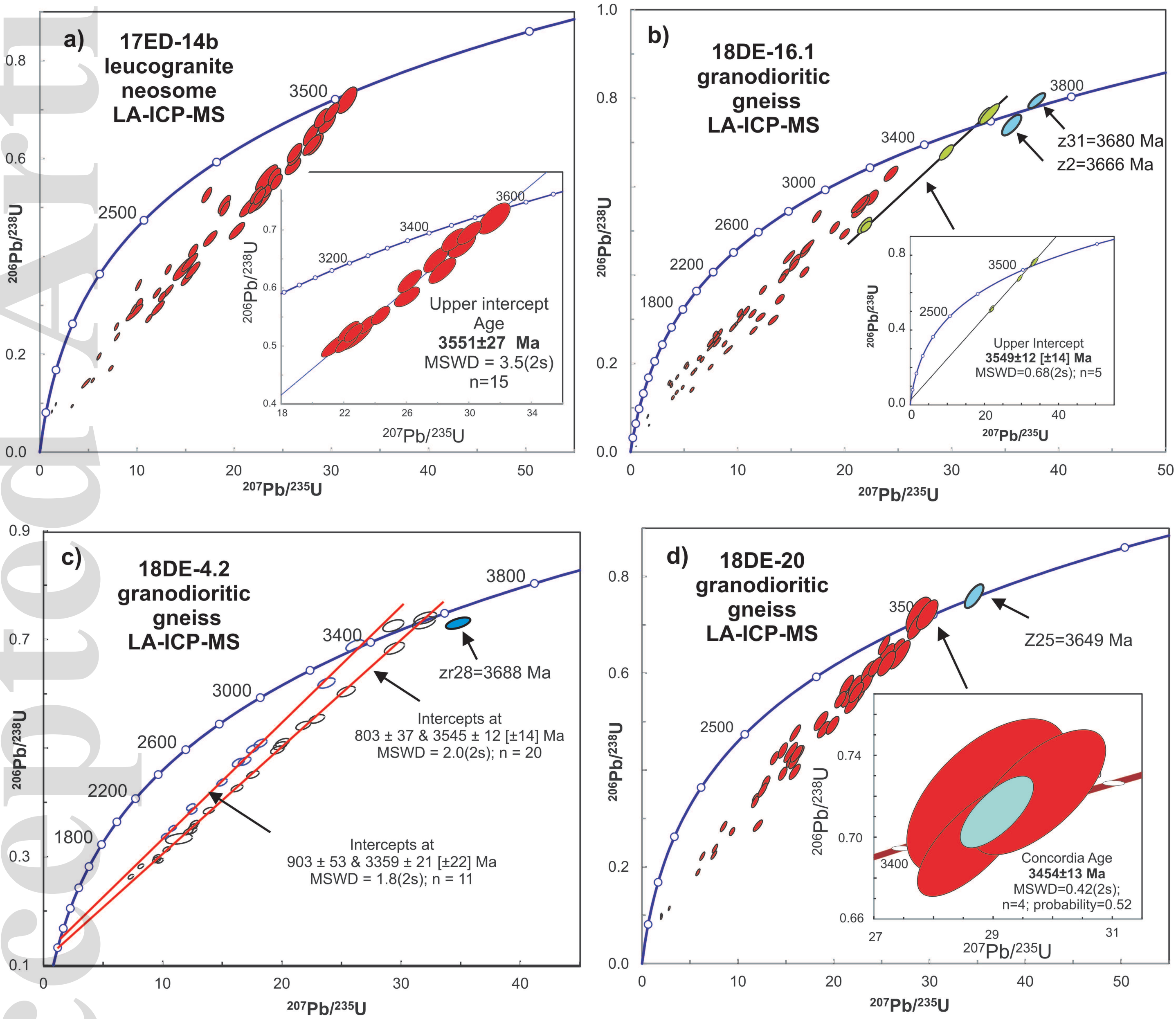


a)
9º
39º
Fig.b
S
G
J
G
BH
S. Francisco River
Belo Horizonte
Salvador
São Francisco Craton
Brazil
0 150 300 km
LEGEND
Phanerozoic cover
Neoproterozoic cover
Mesoproterozoic cover
Archaean-Palaeoproterozoic Itabuna-Salvador-Curaçá orogen
Archaean Jequié granulite complex
Archaean-Palaeoproterozoic gneiss-supracrustal terrains
Craton limit
20º
b)
W40°40' S 11°40'
Piritiba
18DE-1
17ED-14
18DE-16
18DE-17
18DE-20
18DE-4
2 km
W 40°30' S 11°50'
Saude Complex
Mundo Novo Complex
Recent cover
Structural fabrics and foliation
Jacobina Group
Granite
Mairi Complex
Paved road

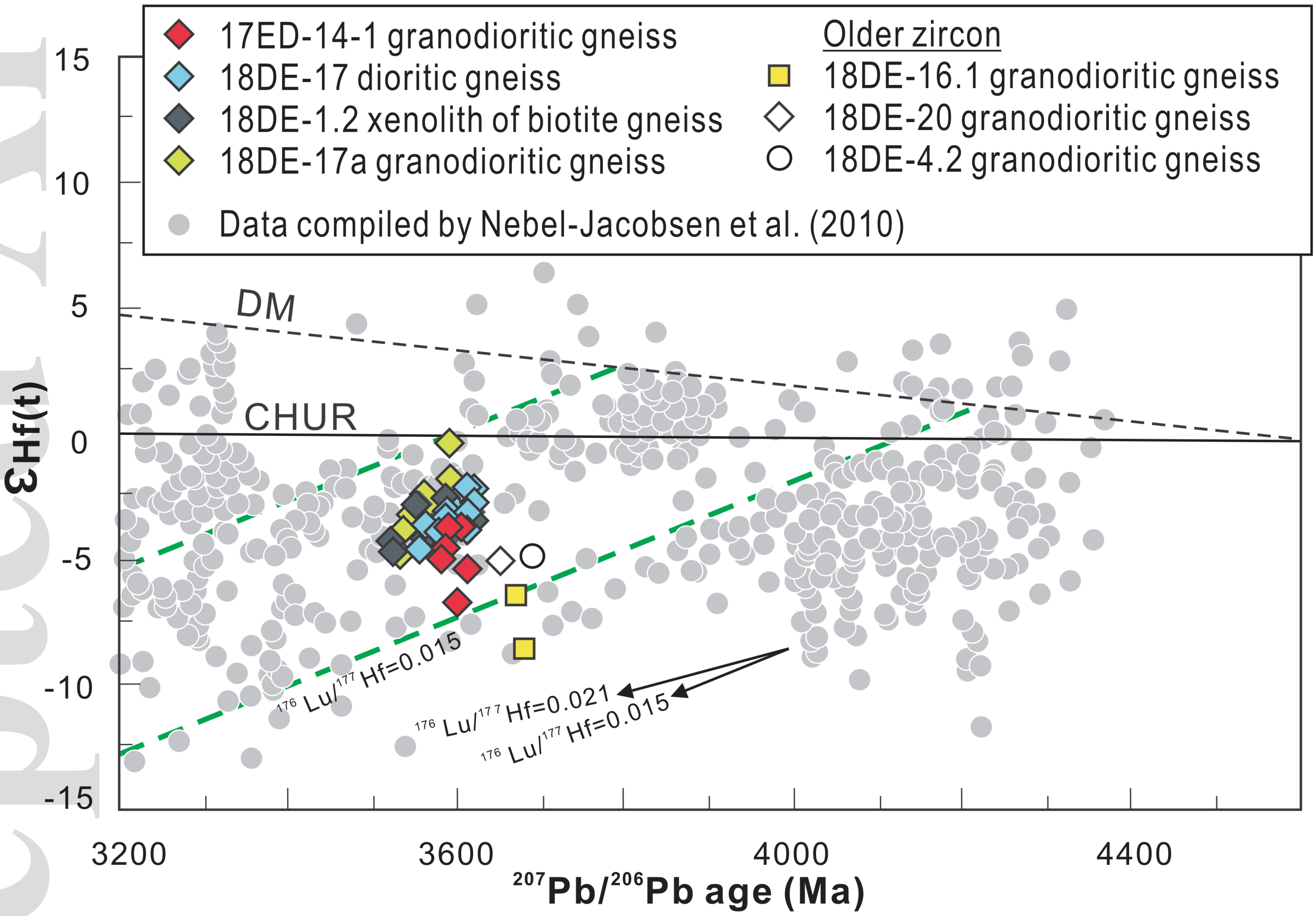

a)
b)
c)
d)

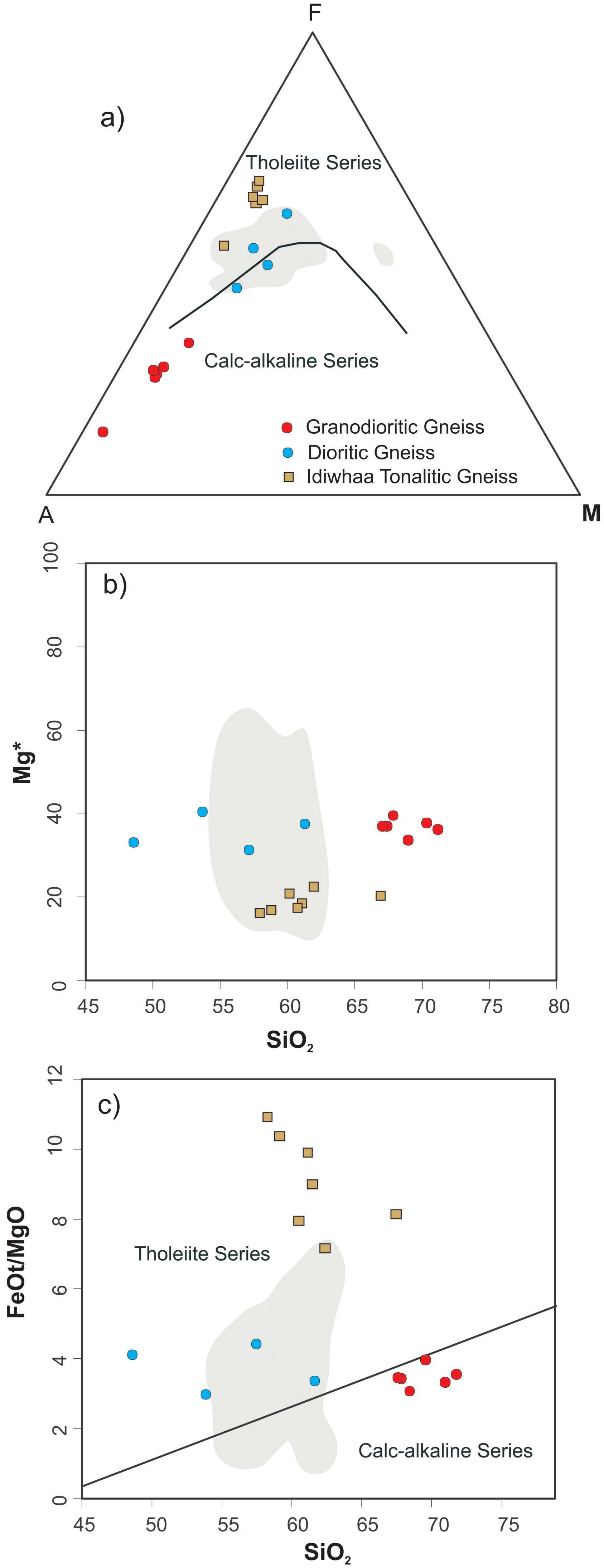


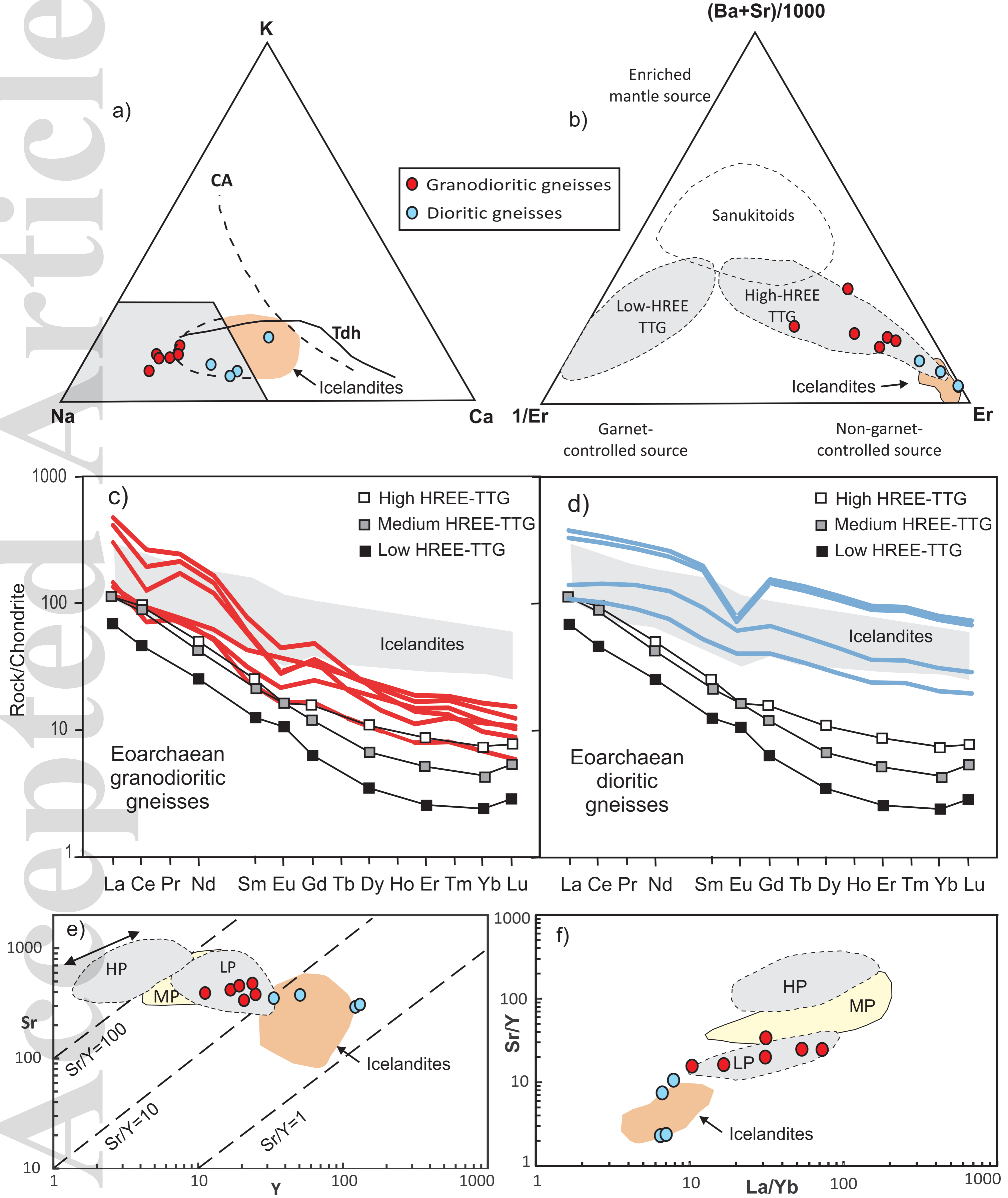
a) 17ED-14.1 granodioritic paleosome LA-ICP-MS
Intercepts at 590±100 & 3622±16 [18] Ma
MSWD = 14(2s)
Upper intercept Age
3626±15 Ma
MSWD=1.09(2s)
b) 17ED-14.1 granodioritic paleosome SHRIMP
Concordia Age
3521±27 Ma
MSWD=0.68(1s); n=3
probability = 0.41
Concordia Age
3619±6.8 Ma
MSWD=2.2(1s); n=3
probability = 0.14
Concordia Age
3642.2±4.7 Ma
MSWD=1.7(1s); n=4
probability = 0.19
c) 18DE-17 dioritic gneiss band LA-ICP-MS
Concordia Age
3627.9 ± 8.6 Ma
MSWD = 0.051(2s); n=8
Probability = 0.82
d) 18DE-17 dioritic gneiss band SHRIMP
Average Age
3513 ± 40 Ma
MSWD = 1.6(1s); n=3
Probability = 0.19
Average Age
3613.5 ± 4.3 Ma
MSWD = 0.89(1s); n=9
Probability = 0.52
Average Age
3637.7 ± 7.7 Ma
MSWD = 0.078(1s); n=3
Probability = 0.92
e) 18DE-17a granodioritic gneiss band LA-ICP-MS
Upper intercept
3598.8±6.8 Ma
n=20, MSWD=1.6(2s)
Upper intercept
3441± 24 Ma
n=3, MSWD=0.112(2s)
f) 18DE-1.2 xenolith of biotite gneiss LA-ICP-MS
Upper intercept
3557±16 Ma
MSWD=2.2
(2s); n=10
data-point error ellipses are 2s
Concordia Age
3609.7 ± 8.5 Ma
MSWD=0.65(2s)
n=6; Probability=0.42
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$



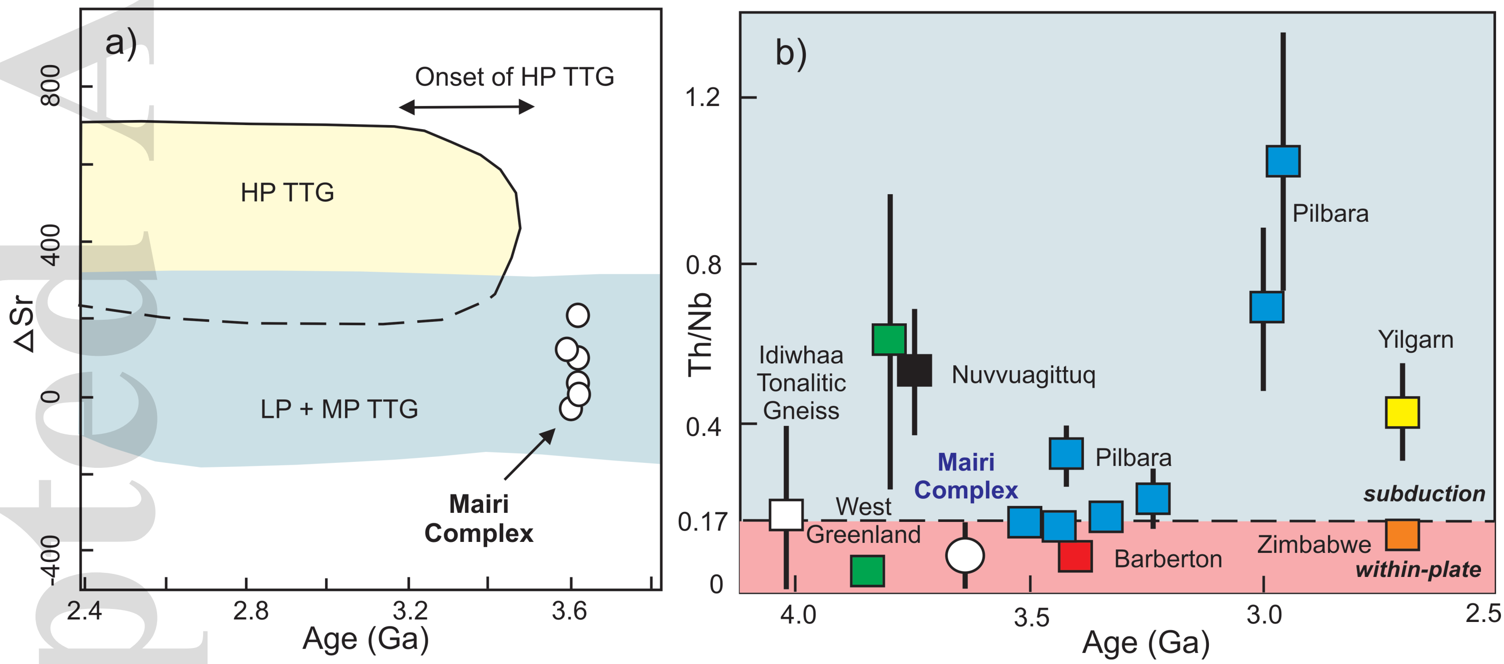
a)
17ED-14b leucogranite neosome LA-ICP-MS
Upper intercept Age
3551±27 Ma
MSWD = 3.5(2s)
n=15
b)
18DE-16.1 granodioritic gneiss LA-ICP-MS
z31=3680 Ma
z2=3666 Ma
Upper Intercept
3549±12 [±14] Ma
MSWD=0.68(2s); n=5
c)
18DE-4.2 granodioritic gneiss LA-ICP-MS
zr28=3688 Ma
Intercepts at
803 ± 37 & 3545 ± 12 [±14] Ma
MSWD = 2.0(2s); n = 20
Intercepts at
903 ± 53 & 3359 ± 21 [±22] Ma
MSWD = 1.8(2s); n = 11
d)
18DE-20 granodioritic gneiss LA-ICP-MS
Z25=3649 Ma
Concordia Age
3454±13 Ma
MSWD=0.42(2s);
n=4; probability=0.52


17ED-14-1 granodioritic gneiss
18DE-17 dioritic gneiss
18DE-1.2 xenolith of biotite gneiss
18DE-17a granodioritic gneiss
Data compiled by Nebel-Jacobsen et al. (2010)
Older zircon
18DE-16.1 granodioritic gneiss
18DE-20 granodioritic gneiss
18DE-4.2 granodioritic gneiss
DM
CHUR
176 Lu/177 Hf=0.015
176 Lu/177 Hf=0.021
176 Lu/177 Hf=0.015
εHf(t)
15
10
5
0
-5
-10
-15
3200
3600
4000
4400
207Pb/206Pb age (Ma)


F
a)
Tholeiite Series
Calc-alkaline Series
Granodioritic Gneiss
Dioritic Gneiss
Idiwhaa Tonalitic Gneiss
A
M
b)
Mg*
0
20
40
60
80
100
45
50
55
60
65
70
75
80
SiO2
c)
FeOt/MgO
0
2
4
6
8
10
12
Tholeiite Series
Calc-alkaline Series
45
50
55
60
65
70
75
SiO2



a)
K
CA
Tdh
Na
Ca
Icelandites
Granodioritic gneisses
Dioritic gneisses
b)
(Ba+Sr)/1000
Enriched mantle source
Sanukitoids
Low-HREE TTG
High-HREE TTG
Icelandites
1/Er
Er
Garnet-controlled source
Non-garnet-controlled source
c)
High HREE-TTG
Medium HREE-TTG
Low HREE-TTG
Icelandites
Eoarchaean granodioritic gneisses
Rock/Chondrite
1000
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
d)
High HREE-TTG
Medium HREE-TTG
Low HREE-TTG
Icelandites
Eoarchaean dioritic gneisses
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
e)
HP
LP
MP
Sr
Y
Sr/Y=100
Sr/Y=10
Sr/Y=1
Icelandites
1000
100
10
1
10
100
1000
f)
HP
MP
LP
Sr/Y
La/Yb
Icelandites
1000
100
10
1
1
10
100
1000



a)
Onset of HP TTG
HP TTG
LP + MP TTG
Mairi
Complex
ΔSr
800
400
0
-400
2.4
2.8
3.2
3.6
Age (Ga)
b)
Th/Nb
1.2
0.8
0.4
0.17
0
Pilbara
Yilgarn
Nuvvuagittuq
Idiwhaa
Tonalitic
Gneiss
Mairi
Complex
Pilbara
West
Greenland
Barberton
Zimbabwe
subduction
within-plate
4.0
3.5
3.0
2.5
Age (Ga)